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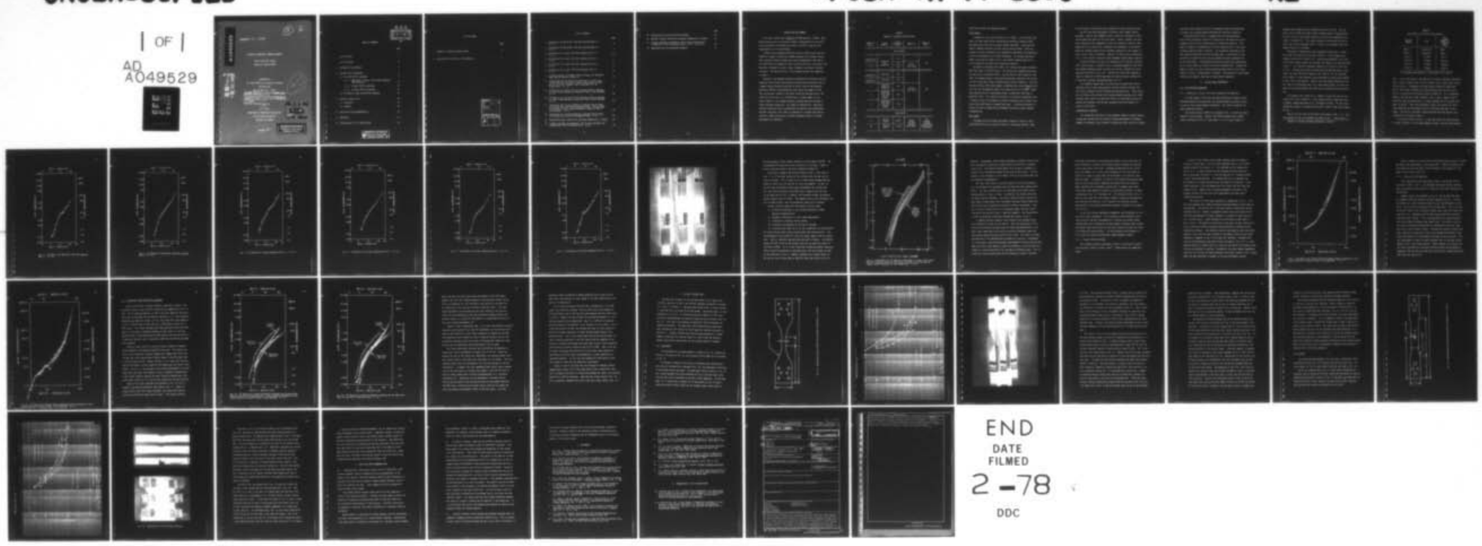

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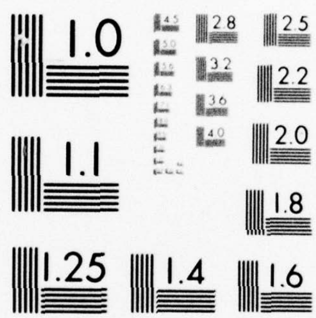

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FATIGUE IN ADHESIVELY BONDED LAMINATES

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by

J. A. Alic

Department of Mechanical Engineering

Wichita State University

Wichita, KS 67208

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1. INTRODUCTION AND SUMMARY

This report covers work supported by AFOSR Grant No. 75-2994. More detailed discussions of portions of these investigations will be found in the references cited below and listed in Section 6, page 42, the Chronological List of Publications.

Fatigue crack propagation (FCP) and fatigue lifetime tests were performed on a number of adhesively bonded aluminum alloy laminate systems. These laminate systems involved two alloys (predominately 7075-T6(51); also 2024-T351), two adhesives (Hysol EA 9410 and AF-55), and several combinations of numbers of layers, layer thickness, and overall laminate thickness. The characteristics of the laminate systems are summarized in Table 1.

Basically, the program consisted of extensions of previous work performed by the Principal Investigator at Wichita State University and as a Summer Faculty Research Associate at the Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson AFB, during the summer of 1975. Thus the two main streams of the study--involving laminates with a few relatively thick layers, or alternatively, a larger number of thin layers (Table 1)--are somewhat tenuously related and were directed at rather different objectives: the former at laminates of a type which could be relatively easily incorporated into more-or-less conventional aircraft structures, the latter at laminates of a perhaps more specialized sort, where the aim was to examine prospective gains in fatigue performance by lamination.

Table 1

Summary of Laminate Systems Tested

<table>
<tr><th>Number of Layers</th><th>Layer Material</th><th>Layer Thickness (in.)</th><th>Adhesive</th><th>Types of Tests</th></tr>
<tr><td colspan="5">THICK LAYERS</td></tr>
<tr><td>1 (monolithic)</td><td rowspan="3">7075-T651 (FDL material)</td><td>1/2</td><td></td><td rowspan="3">FCP</td></tr>
<tr><td>2</td><td>1/4</td><td rowspan="2">AF-55 (FPL etch)</td></tr>
<tr><td>4</td><td>1/8</td></tr>
<tr><td>1 (monolithic)</td><td>2024-T351</td><td>1/4</td><td rowspan="2"></td><td rowspan="5">FCP</td></tr>
<tr><td>1 (monolithic)</td><td>7075-T651</td><td>1/4</td></tr>
<tr><td>2</td><td>2024-T351 bonded to 7075-T6</td><td>1/4</td><td rowspan="3">AF-55 (FPL etch)</td></tr>
<tr><td>4</td><td>2024/7075 with 2024 exterior layers</td><td>1/8</td></tr>
<tr><td>4</td><td>2024/7075 with 7075 exterior layers</td><td>1/8</td></tr>
<tr><td colspan="5">THIN LAYERS</td></tr>
<tr><td>8</td><td>7075-T6 (clad)</td><td>0.035</td><td rowspan="2">Hysol EA 9410 (chromic acid etch)</td><td rowspan="2">FCP; Fatigue Lifetime (notched and unnotched)</td></tr>
<tr><td>22</td><td>7075-T6 (bare)</td><td>0.0115</td></tr>
</table>

Significant results are summarized below:

Thick Layers

Laminates of this type had either 2 or 4 layers. All-7075-T651 laminates cut from larger center-cracked panels previously tested at AFFDL were machined to the form of compact tension specimens. These gave FCP results somewhat different from the earlier tests at AFFDL. While the cause(s) of these differences are incompletely understood, the differences are not large enough to be of great importance. As had been previously found in the tests at AFFDL, both 2- and 4-layer laminates gave FCP results essentially the same as for monolithic material.

Bi-material laminates with either 2 or 4 layers were made by bonding 2024-T351 layers to 7075-T6 layers. FCP results were compared with those for each alloy in monolithic form. The FCP rates of the bi-material laminates fell between those of the baseline monolithic materials, the results for the 2-layer and 4-layer laminates being virtually identical. The more fatigue-resistant 2024 layers appear to dominate the crack propagation process over the intermediate range of ΔK values from 6 to 15 ksi$\sqrt{\text{in}}$, where crack growth rates are considerably closer to monolithic 2024 than to monolithic 7075. This range of ΔK values is of practical importance, both in terms of actual crack growth in aircraft structures and in terms of design calculations based on assumed flaw sizes. It would be desirable to extend this work to aggressive environments and also to other laminate configurations.

Thin Layers

Laminates with thin layers had either 8 layers of 0.035 in. thick clad 7075-T6 alloy or 22 layers of 0.0115 in. thick bare 7075-T6. Both

FCP and fatigue lifetime tests were conducted on these laminate systems.

The FCP tests were performed on relatively small compact tension specimens. Results were somewhat erratic; these are attributed to interactions among the layers as the crack grows. Overall, however, the laminates showed FCP rates comparable to those for monolithic 7075-T6, there appearing to be no particular increments--nor decrements--in FCP performance for through-cracked divider laminates regardless of the numbers of layers used or their thicknesses. However, for other crack orientations--e.g., a crack arrester situation--these parameters would remain important.

Fatigue lifetime tests were also conducted on all-7075-T6 laminates with 8 and 22 layers. Notched as well as unnotched geometries were used, the notched specimens having a central hole giving a theoretical stress concentration factor of $K_t = 2.42$. Laminate S-N curves were compared to those for monolithic 7075-T6 specimens for tension-tension loading with a load ratio (minimum load/maximum load) of $R = 0.1$.

The laminates showed lower S-N curves than for monolithic 7075-T6. Laminates with 22 layers gave generally shorter fatigue lifetimes than the 8-layer laminates for both notched and unnotched tests. These results are at variance with previous fully-reversed bending fatigue tests, where laminates were superior to monolithic 7075-T6 in unnotched form and comparable when notched, with 22-layer laminates having the highest S-N curves in both cases.

Implications of Results

The unexpected inferiority of the laminates tested in tension-tension fatigue may indicate that the fatigue lifetime performance of laminates depends on parameters such as mode of loading and stress ratio to an extent such that results based on one set of parameters cannot be extrapolated to another set using the methods developed for monolithic materials.

Concerning the FCP tests, it appears that for design purposes, crack divider laminates in which all layers are of the same alloy can be assumed to have FCP rates characteristic of monolithic material. This should in general be conservative; FCP rates characteristic of the layer thickness should be used if possible. For bi-material laminates of the type combining 2024-T351 and 7075-T6 tested here, it would again be conservative to assume FCP rates half-way between the rates characteristic of the constituents. The exception would be for growth rates above about 50 μin./cycle, which are closer to the 7075-T6 growth rates. Neither the number of layers nor their relative positions would seem to be of consequence as long as a through-crack is present. The existence of part-through cracks could, however, make both of these factors important.

2. FATIGUE CRACK PROPAGATION

2.1. All-7075-T651 Laminates

2.1.1. Monolithic, 2-Layer, and 4-Layer Laminates (FDL Material)

A limited number of FCP tests have been conducted on compact tension sepcimens machined from monolithic and laminated panels previously tested at the Air Force Flight Dynamics Laboratory. This stock of material has been termed FDL material.

The previous tests at AFFDL are discussed in Ref. 1, which also gives details on the laminates. Briefly, the 7075-T651 panels had a nominal overall thickness of 1/2 in., with either 1, 2, or 4 layers (Table 1).

Laminates were bonded with AF-55 adhesive using an FPL etch. The test panels used at AFFDL had either central through-cracks or through-cracks at holes, with a crack divider orientation (crack front perpendicular to planes of laminae) [1].* The primary purpose of the present work was to verify the results presented in Ref. 1 using a third specimen type--the compact tension (CT) specimen.

Duplicate CT specimen tests were conducted on monolithic, 2-layer, and 4-layer FDL material as outlined in Table 2. The CT geometry was standard, with $H/W = 0.6$ and $W = 4$ in. Testing was performed in air using a 35 kip MTS loading system; the procedure was identical to that described in Ref. 2. This entailed sinusoidal loading at 10 Hz with a load ratio R of 0.1. Fatigue cracks were initiated from the machined slots at high loads, the loads then being reduced to 125 - 1250 lb. for all specimens. Crack lengths, a, were measured using microscopes to read scales attached to each side of the specimen. Because the crack lengths measured on the two sides of the specimens were in all cases nearly equal, only the averages of the two measurements have been used in presenting the results below.

The average crack length (a) vs. number of cycles (N) data was converted to FCP rate, (da/dN) vs. stress intensity factor range (ΔK) using a computer program developed by J.P. Gallagher at AFFDL. FCP rates were determined by means of a movable strip with a 7-point linear least squares fit [2].

Results for FCP tests on FDL material are shown in Figs. 1 - 6. Fracture surfaces of the six specimens are shown in Fig. 7. The results in

*Numbers in brackets designate References, Section 5.

Table 2

Description of FCP Tests on FDL Material

Specimen Number	Type	FDL Specimen Number on Original Panel
MHC-1-1	monolithic	MHC-1
MHC-2-1	monolithic	MHC-2
LCC-2-1-1	2-layer	LCC-2-1
LCC-2-2-1	2-layer	LCC-2-2
LCC-4-0-1	4-layer	unknown
LCC-4-1-1	4-layer	LCC-4-1

All specimens were tested at a load range of 125 - 1250 lb.

Figs. 1 - 6 are consistent in that each pair of similar specimens (monolithic, Figs. 1 and 2; 2-layer, Figs. 3 and 4; 4-layer, Figs. 5 and 6) gave closely similar results. Furthermore the three types of materials--monolithic, plus 2- and 4-layer laminates--all gave essentially the same FCP rates. This is in accord with the previous tests at AFFDL [1]. It is noteworthy, however, that the two 4-layer laminates, Figs. 5 and 6, showed slightly lower FCP rates than monolithic or 2-layer specimens for ΔK's greater than about 10 ksi$\sqrt{in}$. While the difference is small, FCP results for both 4-layer specimens are below those for any of the other specimens in this range. This may be a thickness effect associated with the smaller layer thicknesses as discussed in Ref. 3.

It can also be seen in Figs. 1 - 6 that the results for each specimen in terms of da/dN vs. ΔK are approximately bilinear, with the break between

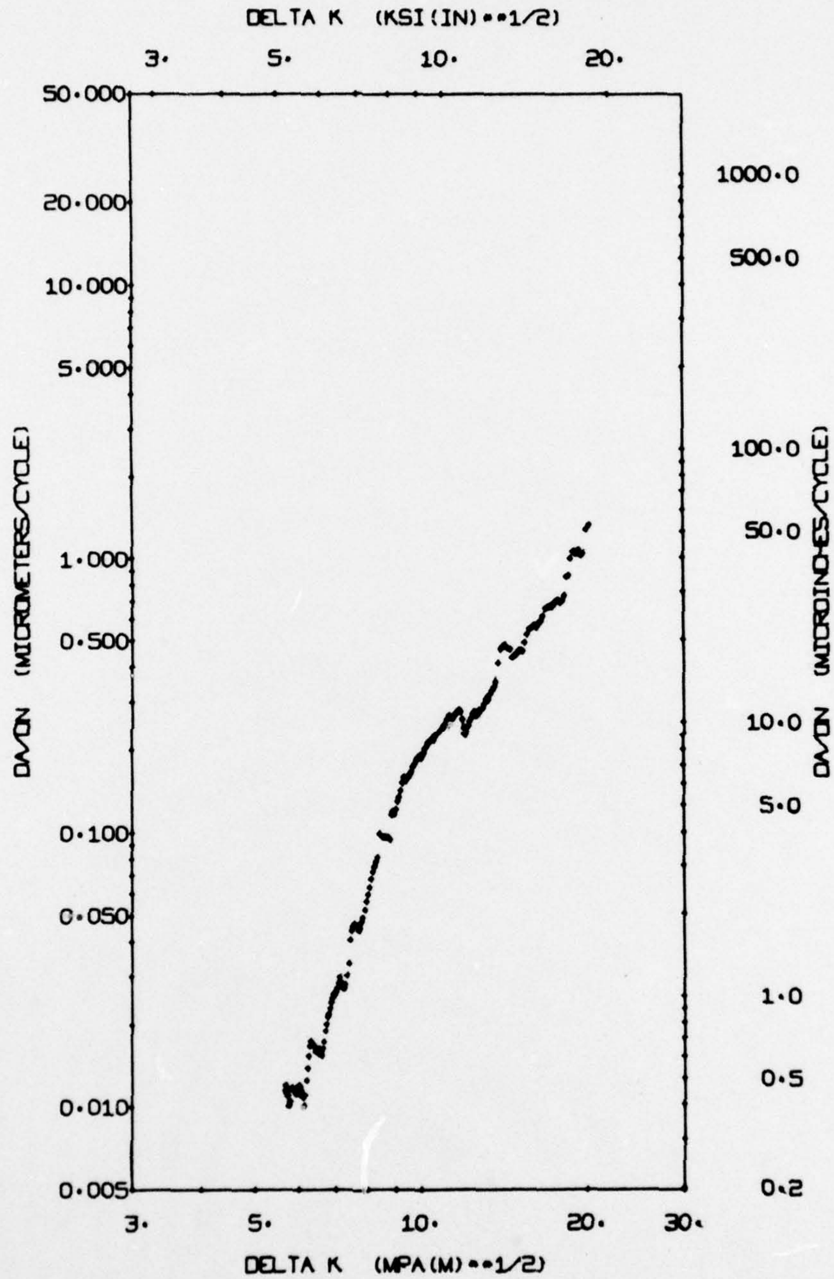

Fig. 1. FCP Results for Monolithic 7075-T651 Specimen MHC-1-1. R = 0.1.

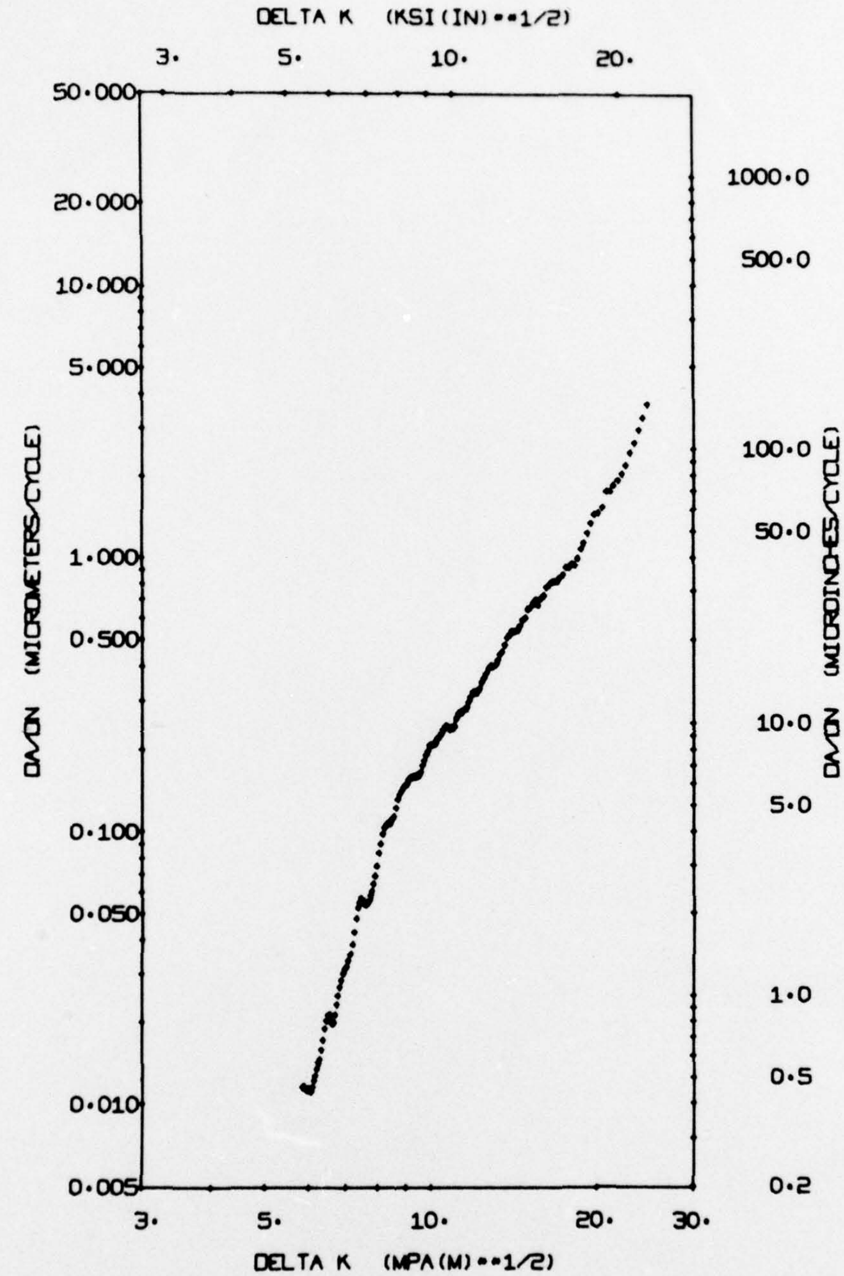

Fig. 2. FCP Results for Monolithic 7075-T651 Specimen MHC-2-1. R = 0.1.

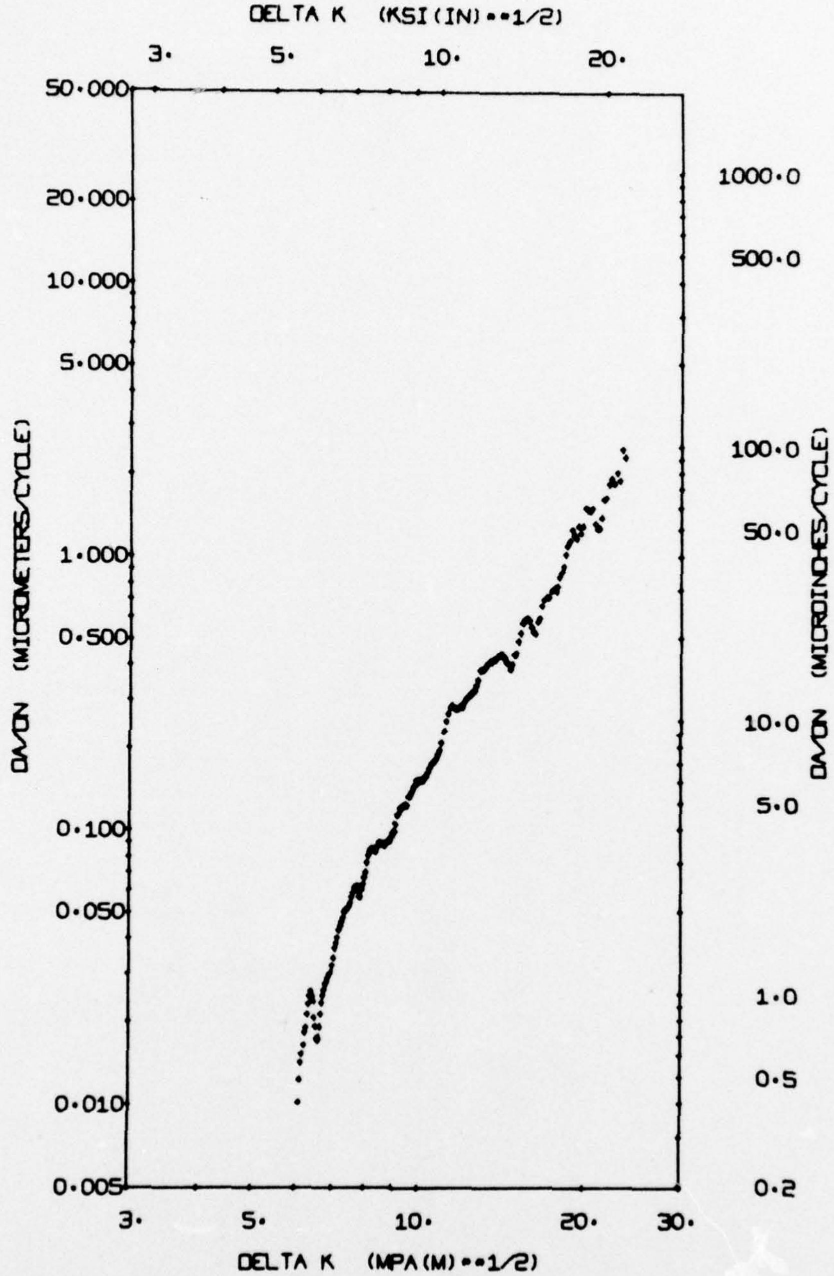

Fig. 3. FCP Results for 2-Layer Laminate LCC-2-1-1. R = 0.1.

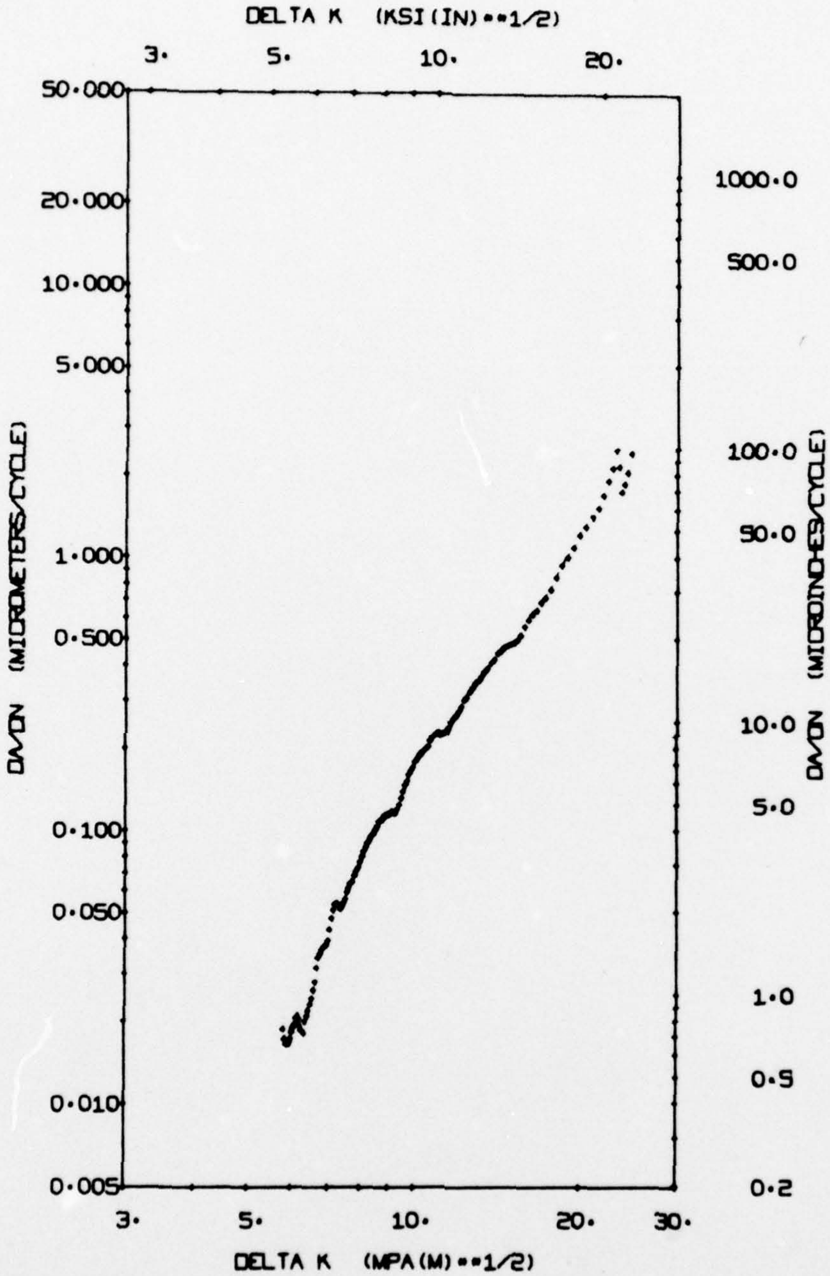

Fig. 4. FCP Results for 2-Layer Laminate LCC-2-2-1. R = 0.1.

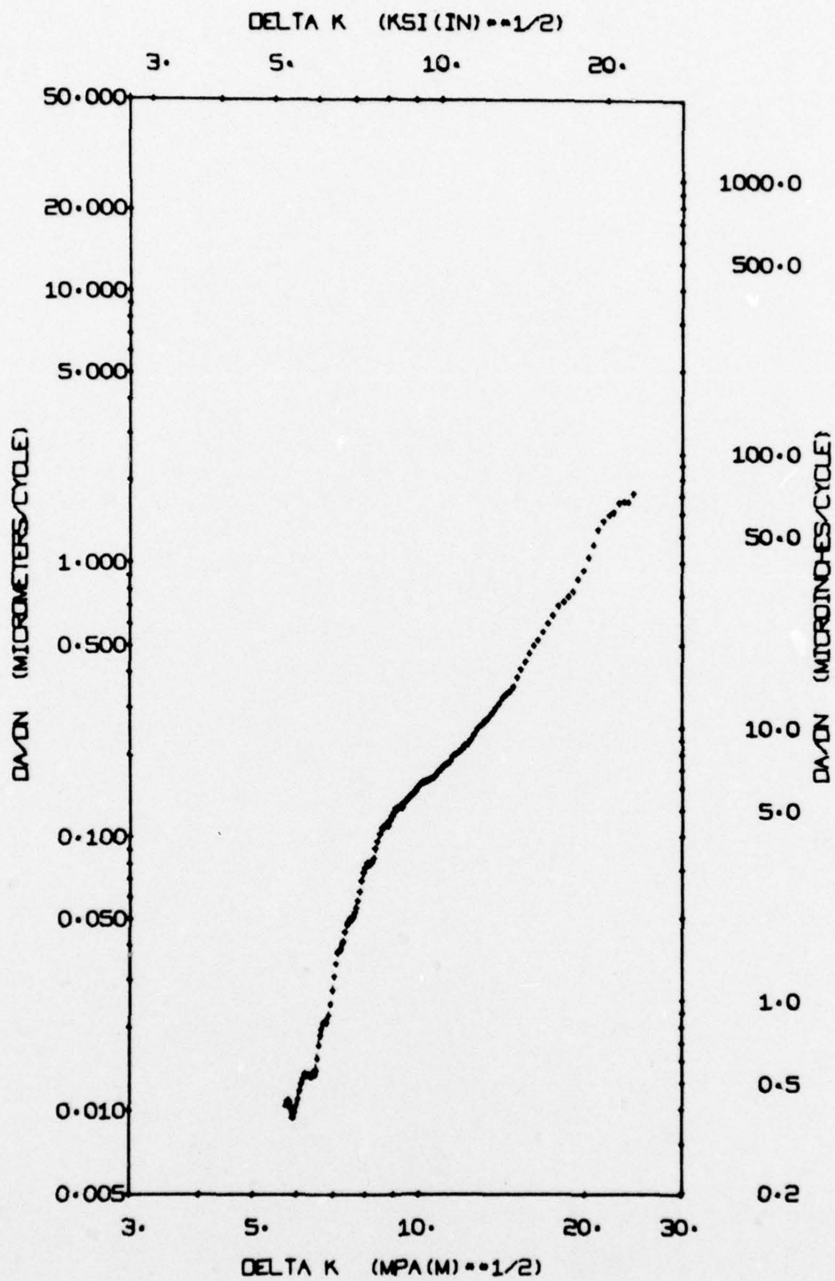

Fig. 5. FCP Results for 4-Layer Laminate LCC-4-0-1. R = 0.1.

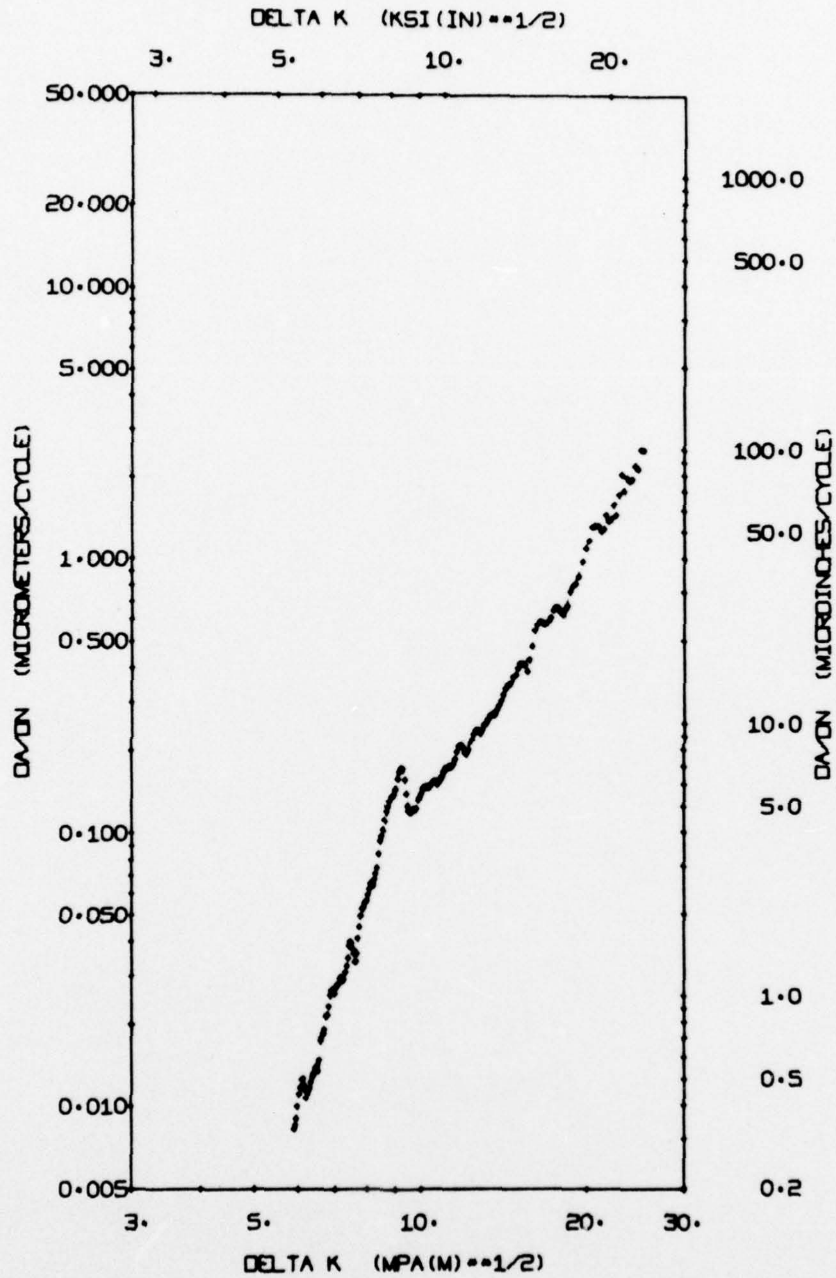

Fig. 6. FCP Results for 4-Layer Laminate LCC-4-1-1. R = 0.1.

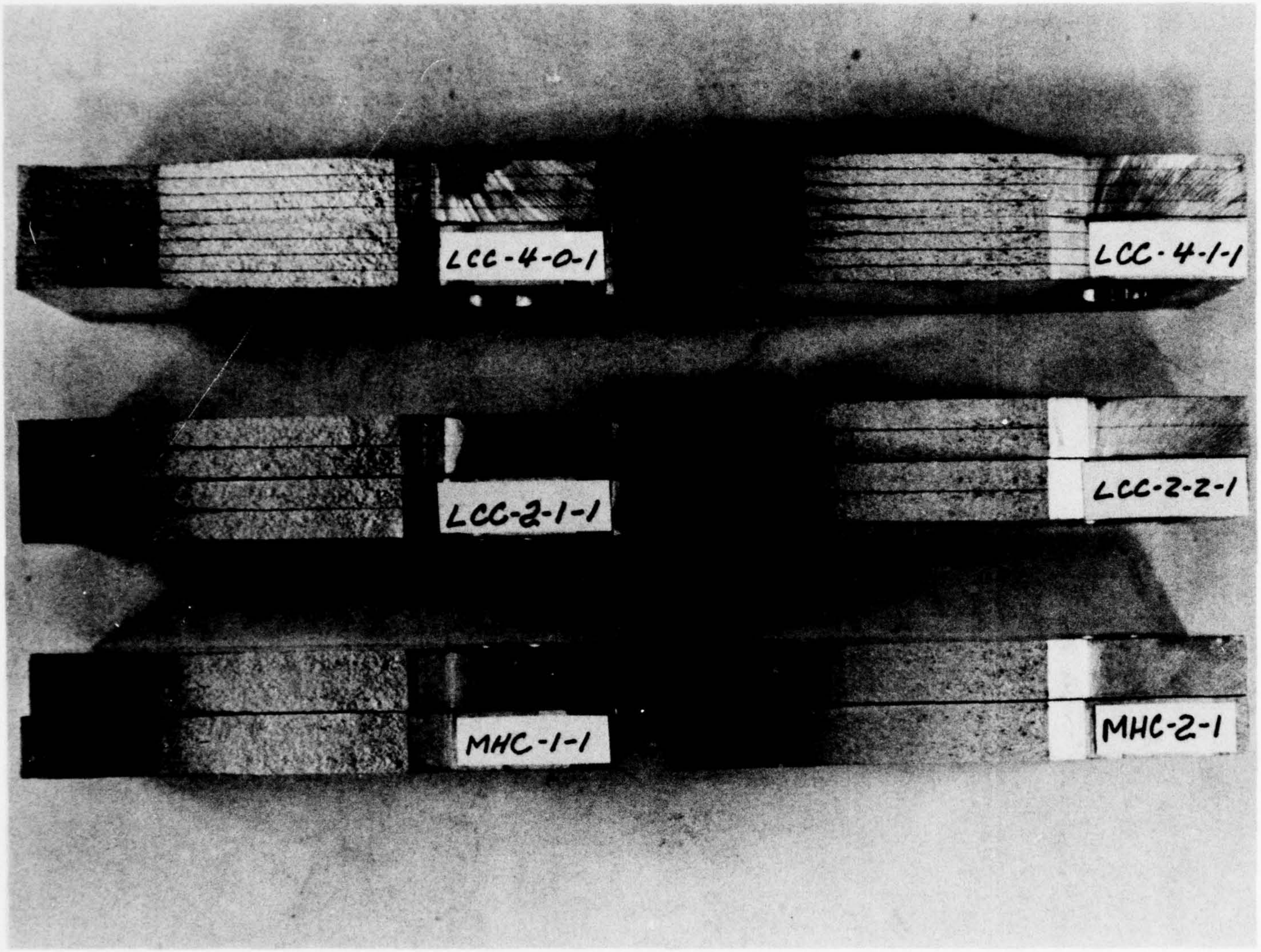

Fig. 7. Fracture Surfaces of Compact Tension Fatigue Test Specimens made from FDL Material (Table 2).

the two nominally linear regions falling at a ΔK of about 8 ksi$\sqrt{in}$. The corresponding FCP rates are in the vicinity of 5 μin./cycle. Again, a similar trend was found in the tests conducted at AFFDL [1].

Continuing to compare the previous results in Ref. 1 with those in Figs. 1 - 6, in the lower portion of the bilinear plots the two sets of results coincide. This is shown in Fig. 8, where bands encompassing the ranges of results for the two sets of tests are compared. In fact, at low FCP rates the present results show considerably less scatter and fall well within the band of the AFFDL tests, though at the low side. In the upper part of Fig. 8, however, the two bands diverge, the present results showing lower FCP rates. This appears to be a real difference, not due to random scatter; thus the prospective causes are of interest.

Several possible reasons for this behavior can be listed:

a) a possible difference in test system calibration or other operating characteristics.

b) systematic differences in crack length measurements.

c) differences in humidity during testing.

d) differences attributable to the type of specimen.

It is unlikely that items (a) or (b) are responsible for the different FCP trends because these trends diverge rather than being parallel. The correspondence at the lowest FCP rates also argues against such an explanation. Item (c)--humidity--may have had some small influence. The humidity ranged from 20% to 40% for the present tests but was generally higher in the tests at AFFDL. As it is well known that increasing humidity adversely affects the FCP performance of aluminum alloys, this may account for some of the difference in Fig. 8. However, humidity has a greater effect on FCP rate at low ΔK values than at high [4], while the trend in Fig. 8 is

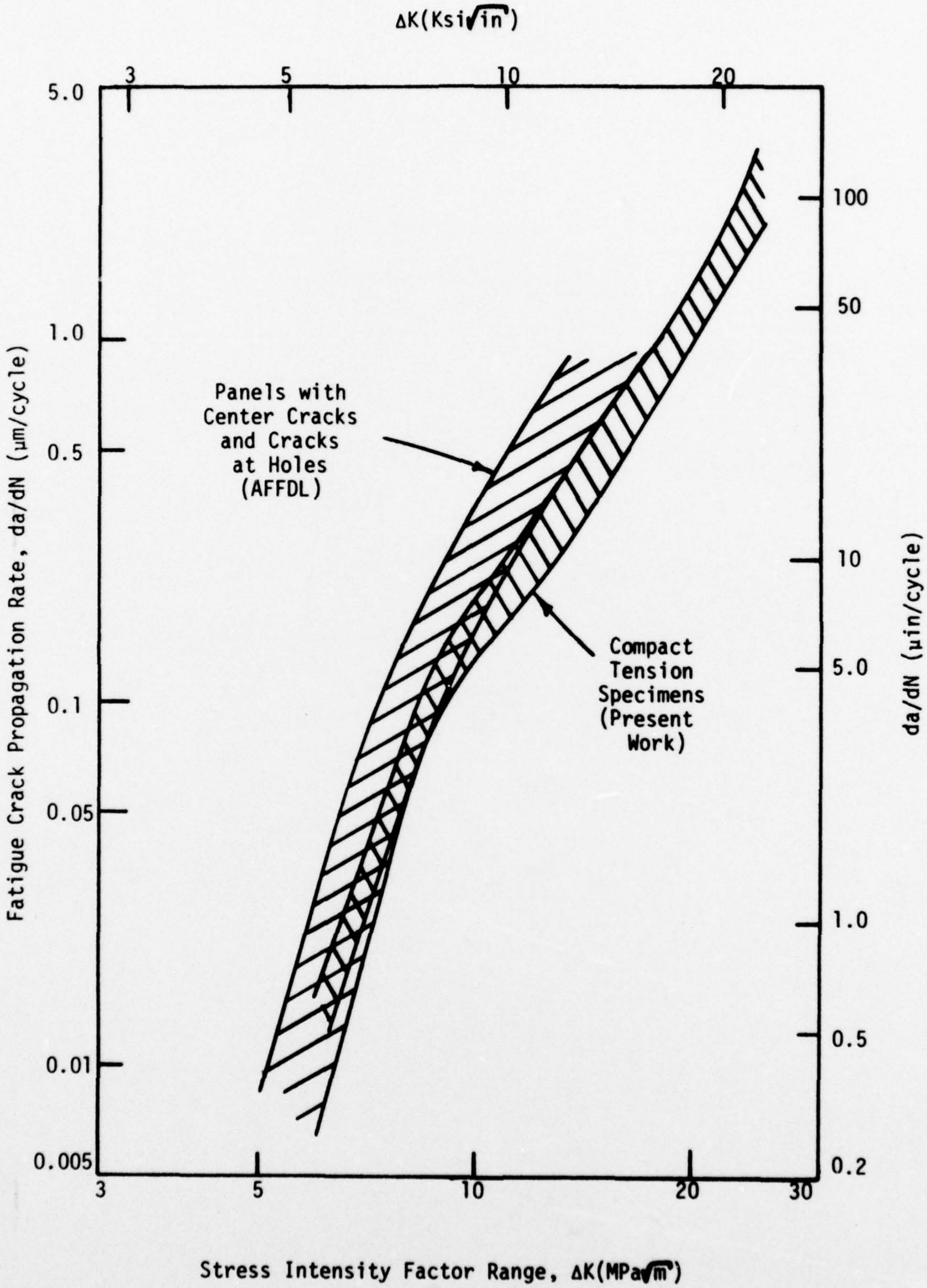

Fig. 8. Scatterbands for FCP Results on Monolithic, 2-Layer, and 4-Layer 7075-T651 Specimens Tested as Wide Panels at AFFDL and in the Form of Compact Tension Specimens for the Present Work. R = 0.1.

opposite. Furthermore, rather larger differences in humidity than existed here are generally required for marked effects on FCP rate in aluminum alloys [4,5]. Thus humidity would appear to be at most a secondary influence on the differences between the two sets of FCP results. The difference in test frequency--5 Hz at AFFDL, 10 Hz for the present work--can be considered inconsequential.

The final item listed as a possible cause of FCP rate differences--(d), the different test specimens--may also have had some, probably small, effect. The tests at AFFDL used 6 in. wide panels with either central through-cracks or cracks at holes. In contrast, the present tests were on compact tension specimens. The stress intensity factor solutions for both center-cracked panels and CT specimens have been widely checked and verified and can be regarded as accurate to within a few percent. That for a crack at a hole may not be as accurately known, but only a small fraction of the results in Ref. 1 used this geometry. Thus inaccuracies in the K calibrations cannot have affected the results in Fig. 8.

It remains possible, however, that different test specimens might give different FCP rates for the same ΔK. While the equivalence of FCP results from different specimen types has often been demonstrated in the past, these comparisons have typically involved considerably fewer and more widely spaced data points than for Fig. 8 [6]. This leads to greater uncertainties in the determination of da/dN for a given ΔK. Furthermore, it is now known, from both experimental measurement [7] and calculation [8], that the plastic zones ahead of cracks are different in size--and thus presumably in strain distribution--for specimens of different types. This includes the center-cracked panels and CT specimens of specific interest.

As fatigue crack growth is associated with plastic flow at the crack tip, these differences in plastic zone character might reasonably be expected to have some effect on FCP rate. Although the magnitude of any such effects are unknown, it is likely that differences in FCP rates would be greater for larger ΔK values where the differences in the plastic zones would be larger. In addition, at high ΔK's the fatigue crack growth might begin to have a quasistatic component associated with crack growth by modes characteristic of monotonic loading [2]; it appears that stable crack growth under monotonic loading is significantly different in center-cracked panels than in CT specimens [8]. The diverging trends in Fig. 8 would be consistent with such effects, though it cannot be concluded with any certainty that they are in fact caused by the different specimen types because of the other uncontrolled variables involved in the comparison in Fig. 8.

In any case, from an engineering standpoint, the differences in Fig. 8 are not of great consequence. This is because in making design calculations based on such data the geometries of interest are neither center-cracked panels nor CT specimens, but more complex situations where neither the nominal loads and stresses nor the stress intensity factors are likely to be known with great accuracy. For such purposes the differences in Fig. 8 and their possible explanations become somewhat academic.

2.1.2. 8-Layer 7075-T6 Laminates

This laminate system is described in Table 1, while the FCP results are discussed in detail in Refs. 3 and 9. These results are summarized below.

A total of five 8-layer crack divider laminates were FCP tested at a variety of load levels. All tests were performed using a 2 1/2 kip MTS loading system at 20 Hz and $R = 0.1$. The specimens were of compact form with $W = 2$ in. In other respects the test procedure and data reduction were as described in Section 2.1.1 with the addition of a secondary method of crack length determination. This method made use of a standard fracture mechanics clip gage attached across the mouth of the specimen. Crack lengths measured in this way compared well with those from the visual measurements [3,9]. However the clip gage measurements were made at less frequent intervals and only the visual measurements have been used in interpreting the data.

FCP results for the 8-layer specimens are summarized in Fig. 9. This plot uses average crack lengths determined from measurements on both sides of the specimens. The results fall in the range typical of monolithic 7075-T6 aluminum alloy [3]. However, considerable side-to-side crack length differences were encountered in 8-layer laminates, in contrast to those with only 2 or 4 thicker layers. These differences are discussed at some length in Refs. 3 and 9. They appear to result mainly from layer-to-layer interactions as the crack front locally accelerates and decelerates at different points through the thickness. This behavior would be accentuated by both the greater number of layers and the lower strength of the adhesive used for the 8-layer laminates as compared to the 2- and 4-layer FDL laminates. Although these side-to-side differences cause more erratic FCP behavior (Fig. 9)--i.e., more apparent scatter in growth rates for a given ΔK--the overall FCP trends are consistent from specimen to specimen. Averaging of the crack lengths compensates quite well for the side-to-side differences, the 8-layer results in Fig. 9 being about the same regardless of whether or not such differences existed.

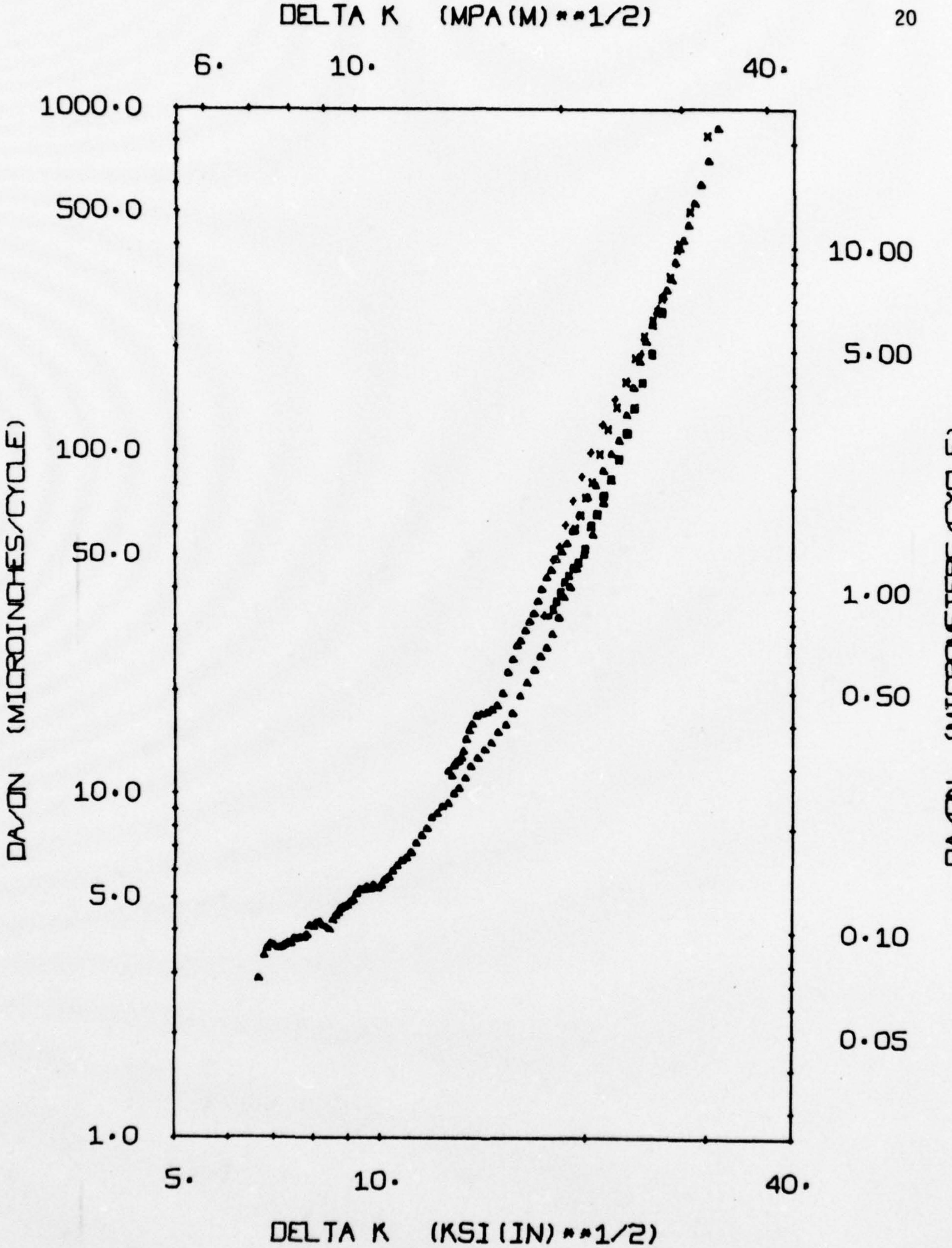

Fig. 9. FCP Results for 8-Layer 7075-T6 Laminates Based on Averages of Crack Lengths Measured on Opposite Sides of Each Specimen. R = 0.1.

Several instances of crack arrest at relatively high ΔK values (7 ksi$\sqrt{in}$ and above) were encountered in the 8-layer tests. These are believed to be associated with the transitions from flat modes of crack growth to slant modes in the various layers [3].

2.1.3. 22-Layer 7075-T6 Laminates

These laminates are also described in Table 1 and the FCP results discussed in Refs. 3 and 9. Five specimens were again tested, the equipment and procedure being identical to those for the 8-layer laminates discussed above.

Summary results are presented in Fig. 10. The 22-layer FCP rates are somewhat lower than those for 8-layer laminates (Fig. 9). This may be evidence of a small thickness effect [3], but the differences are not large. No crack arrests occurred in the 22-layer tests. This is the reason the FCP rates in Fig. 10 extend to lower levels than for 8-layer laminates (Fig. 9). Nonetheless the 22-layer results show more variability than the 8-layer results. This is caused primarily by large and persistent crack length differences from side-to-side. The cracks in the surface layers accelerate and decelerate as influenced by the crack front positions in the 20 interior layers. Although the fracture surfaces show that a nominally uniform crack front exists through-the-thickness [3,9], there would appear to be considerable variations on the microscale. Thus the large number of layers in these laminates leads to even more erratic behavior than in the 8-layer material. Again, however, the results from the various specimens are consistent with one another and are generally comparable with FCP rates for monolithic 7075-T6 alloy, though being somewhat lower than typical [3].

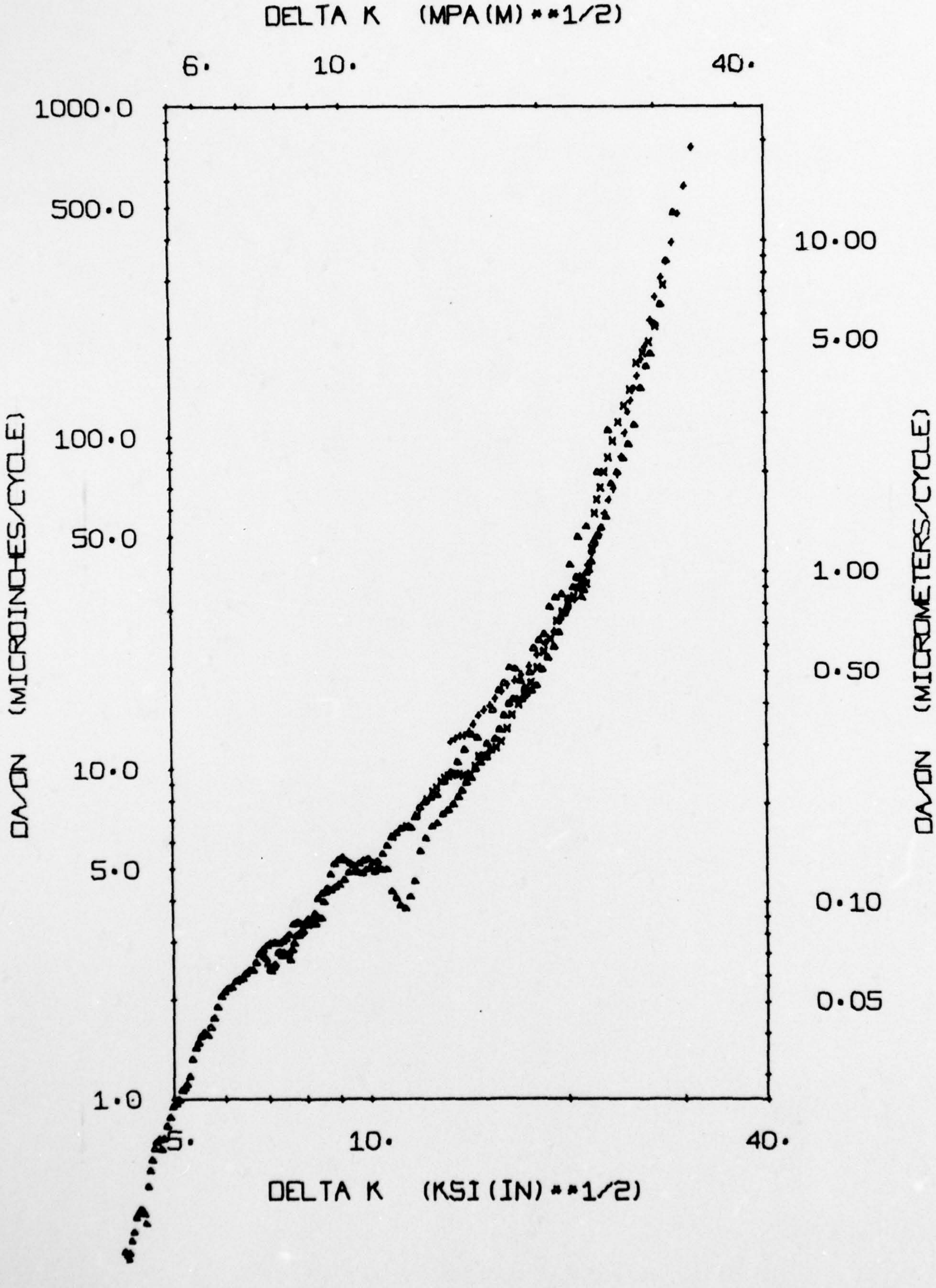

Fig. 10. FCP Results for 22-Layer 7075-T6 Laminates Based on Averages of Crack Lengths Measured on Opposite Sides of Each Specimen. R = 0.1.

2.2. Bi-Material 2024-T351/7075-T6 Laminates

Results of FCP tests on these laminates, described in Table 1, are discussed in Refs. 2 and 10 and will again only be summarized in this report. The CT specimen geometry, as well as the test apparatus and procedure, were as described for FDL material (Section 2.1.1). The bi-material laminates were made with either a 1/4 in. thick 2024-T351 layer bonded to a 1/4 in. 7075-T6 layer or with two 1/8 in. 2024 layers and two 1/8 in. 7075 layers. The 4-layer specimens were fabricated with either both 2024 layers in the middle, sandwiched between the 7075 layers, or with the two 7075 layers in the middle and the 2024 layers on the outside (Table 1). In addition, baseline tests on monolithic 2024-T351 and 7075-T6 specimens were conducted.

Figure 11 shows results for the two 2-layer bi-material laminates tested compared to the baseline monolithic FCP rates. The fracture surfaces of the bi-material laminates showed that stepped crack fronts had existed, the cracks always being slightly longer in the 7075 layer than in the 2024 layer [2,10]. However the basic a vs. N data [10] indicates that the difference in crack length did not depend upon the overall crack length. For Fig. 11, the averages of the surface measurements in the two layers have been used; these appear to give a reasonable representation of the overall behavior because the crack length differences were relatively small (0.04 - 0.21 in.) and did not increase as the crack grew [2].

Results for 4-layer laminates are presented in Fig. 12; also included is the baseline monolithic data shown in Fig. 11. Figure 12 groups results from five 4-layer specimens, two having 7075 exterior layers and three having 2024 exterior layers. The fracture surfaces

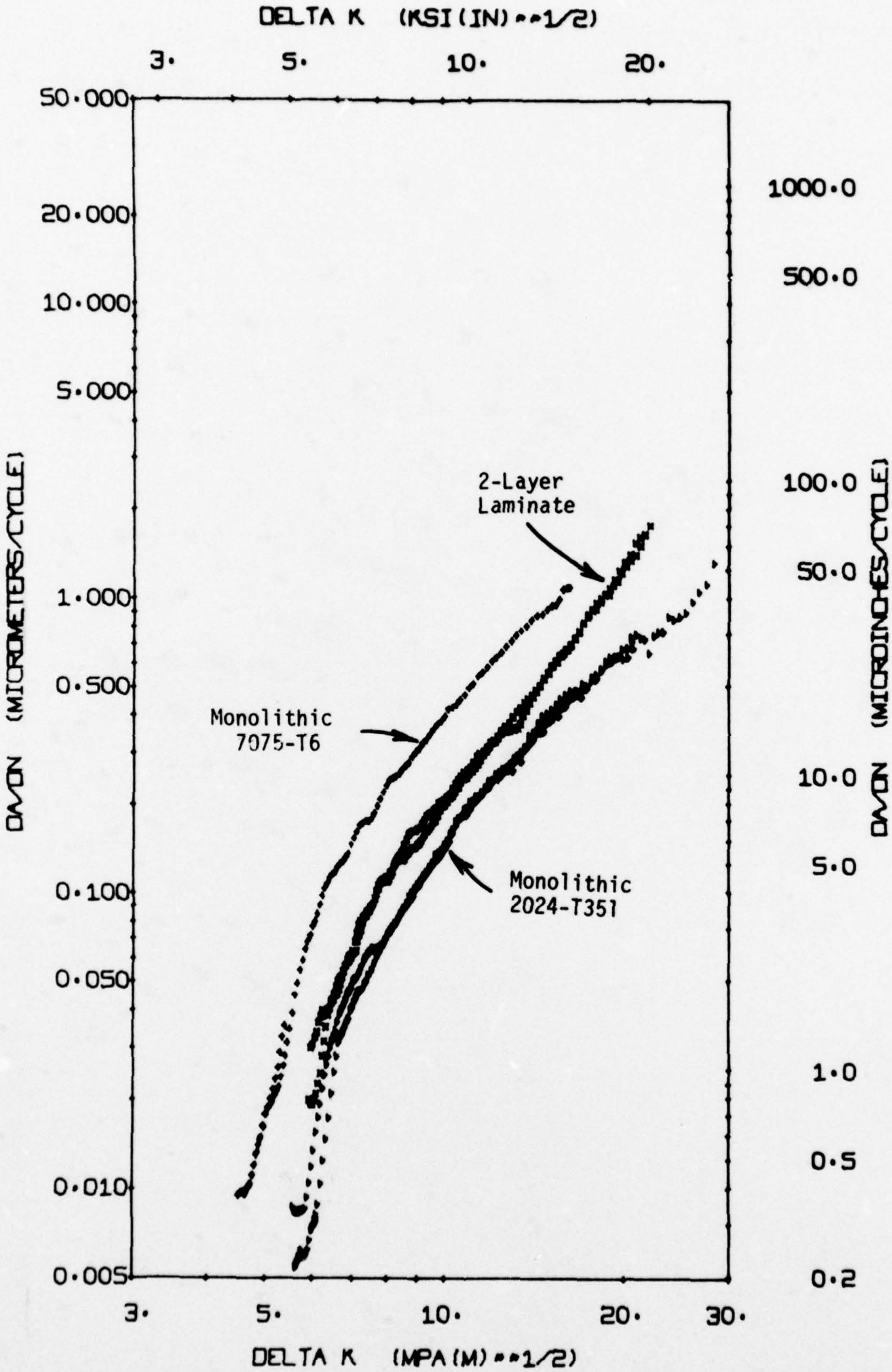

Fig. 11. FCP Results for 2-Layer Bi-Material Laminates and for Monolithic 2024-T351 and 7075-T6 Aluminum Alloys. Results Based on Averages of Crack Lengths Measured on Opposite Sides of Each Specimen. R = 0.1.

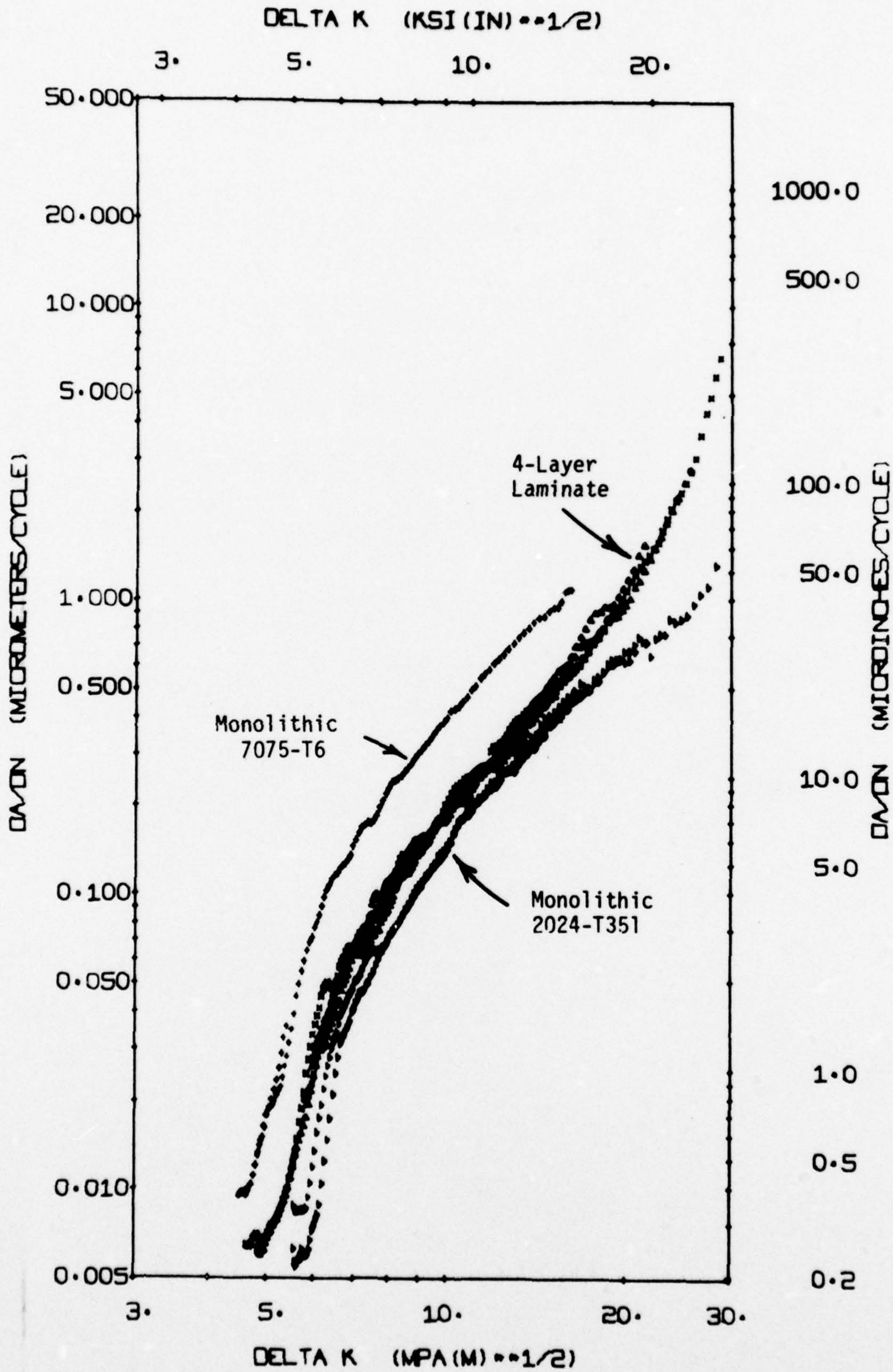

Fig. 12. FCP Results for 4-Layer Bi-Material Laminates and for Monolithic 2024-T351 and 7075-T6 Aluminum Alloys. R = 0.1.

again show that the cracks were always the longest in the 7075 layers. However, when the crack lengths measured on the specimen surfaces are adjusted to compensate for this difference, the results are the same (Fig. 12) regardless of the relative locations of the two alloys. The crack length adjustment entailed measuring the crack lengths at the fracture points for each specimen and using the differences between exterior and interior layers as a correction term added to or subtracted from the surface crack length measurements [2].

Figures 11 and 12 demonstrate that: (a) 2-layer and 4-layer bi-material laminates give essentially the same FCP performance, (b) the relative positions of the two alloys in the 4-layer laminates are immaterial provided the appropriate crack lengths are used in reducing the data, and (c) the bi-material laminate results are closer to the monolithic 2024-T351 trend than to that for monolithic 7075-T6 over much of the ΔK range.

The latter observation indicates that the 2024 has the dominant influence for low to intermediate ΔK values--6 to 15 ksi$\sqrt{in}$. Note that, because the axes of the figures are logarithmic, the laminate growth rates are actually closer to the 2024 rates than might at first appear. Thus the laminate growth rates are considerably less than the averages of the two constituents. It appears that this phenomenon might result from a suppression of the contribution to fatigue crack growth in the 7075-T6 layer of what are often termed static fracture micromechanisms--e.g., microvoid coalescence [2]. Suppression of such mechanisms in the more brittle 7075-T6 may be caused by the restraining effect of the tougher 2024-T351. The 2024 layers, containing the shorter cracks, could act to reduce the crack tip opening displacements (CTOD) in the 7075 layers. As static mechanisms might be expected to become operative only at some critical CTOD, their contributions to crack growth in the 7075 layers might be reduced or eliminated [2].

For ΔK values both above and below this intermediate 6 - 15 ksi$\sqrt{in}$ range, the bi-material laminate rates are more nearly the averages of the constituents, and at the high end, even approach the 7075 trend (Figs. 11 and 12). However the high ΔK data for the baseline materials is limited and should not be extrapolated. Thus it is difficult to evaluate the significance of the behavior of the laminates in this region. For ΔK values below about 6 ksi$\sqrt{in}$ the laminate FCP rates (in this region primarily for 4-layer specimens) are about halfway between those of the baseline alloys. This is not inconsistent with the discussion above, as static fracture mechanisms in the 7075 layers might be supposed to contribute to fatigue crack growth only above some critical stress intensity (which would be directly related to the critical CTOD). Then in the low ΔK region, where K_{max} was below this critical value, there would be no contribution to FCP by static micromechanisms in either monolithic or laminated materials. In this case the laminate FCP rates would be just the averages of those for the monolithic constituents.

Figures 11 and 12 also show that the bi-material laminates exhibit somewhat more scatter in FCP rates than these alloys in monolithic form. This is probably the result of interactions between the layers, as discussed above for all-7075-T6 laminates. Note that the 4-layer results (Fig. 12) are, as expected, somewhat more erratic than the 2-layer results (Fig. 11).

3. FATIGUE LIFETIME TESTS

Specimens for fatigue life testing had either 8 or 22 layers (all-7075-T6), identical to the 8- and 22-layer laminates discussed in Sections 2.1.2 and 2.1.3 (Table 1). Laminates were tested in air in either notched or unnotched form, using the 35 kip MTS system. Load ratios were 0.1, with frequencies of 5 - 8 Hz. If failure did not occur before 5×10^6 cycles, tests were terminated and are noted as runouts on the S-N curves (Figs. 14 and 17). Tests were also conducted on monolithic 7075-T6 specimens for comparative purposes. The monolithic 7075-T6 came from the same plate that provided the 7075 layers for the bi-material laminates discussed in Section 2.2. Fatigue lifetime tests had also been planned on a limited number of specimens cut from the stock of 2- and 4-layer FDL material; however sufficiently large pieces for this purpose were not salvaged.

3.1. Unnotched

The unnotched test specimen geometry is shown in Fig. 13. Results are given as S-N curves in Fig. 14, while typical failure modes are illustrated in Fig. 15.

The fatigue lifetimes of both types of laminates were significantly less than for the monolithic specimens (Fig. 14), the differences increasing as the maximum stress decreased. The monolithic 7075-T6 results in Fig. 14 are in good agreement with published data for this alloy and stress ratio [11] and thus can be considered to provide a valid comparison. At the same time, it is instructive to compare all of the results in Fig. 14 with a large collection of 7075-T6 data for the slightly lower stress ratio of

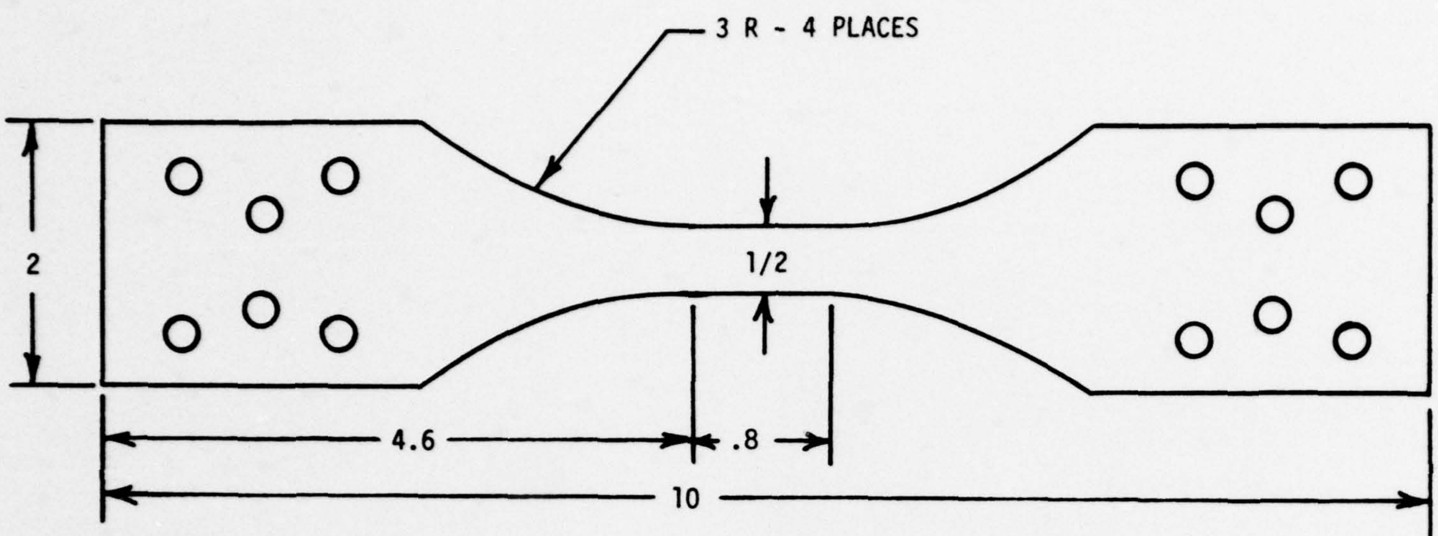

Fig. 13. Unnotched Fatigue Lifetime Test Specimen (dimensions in inches).

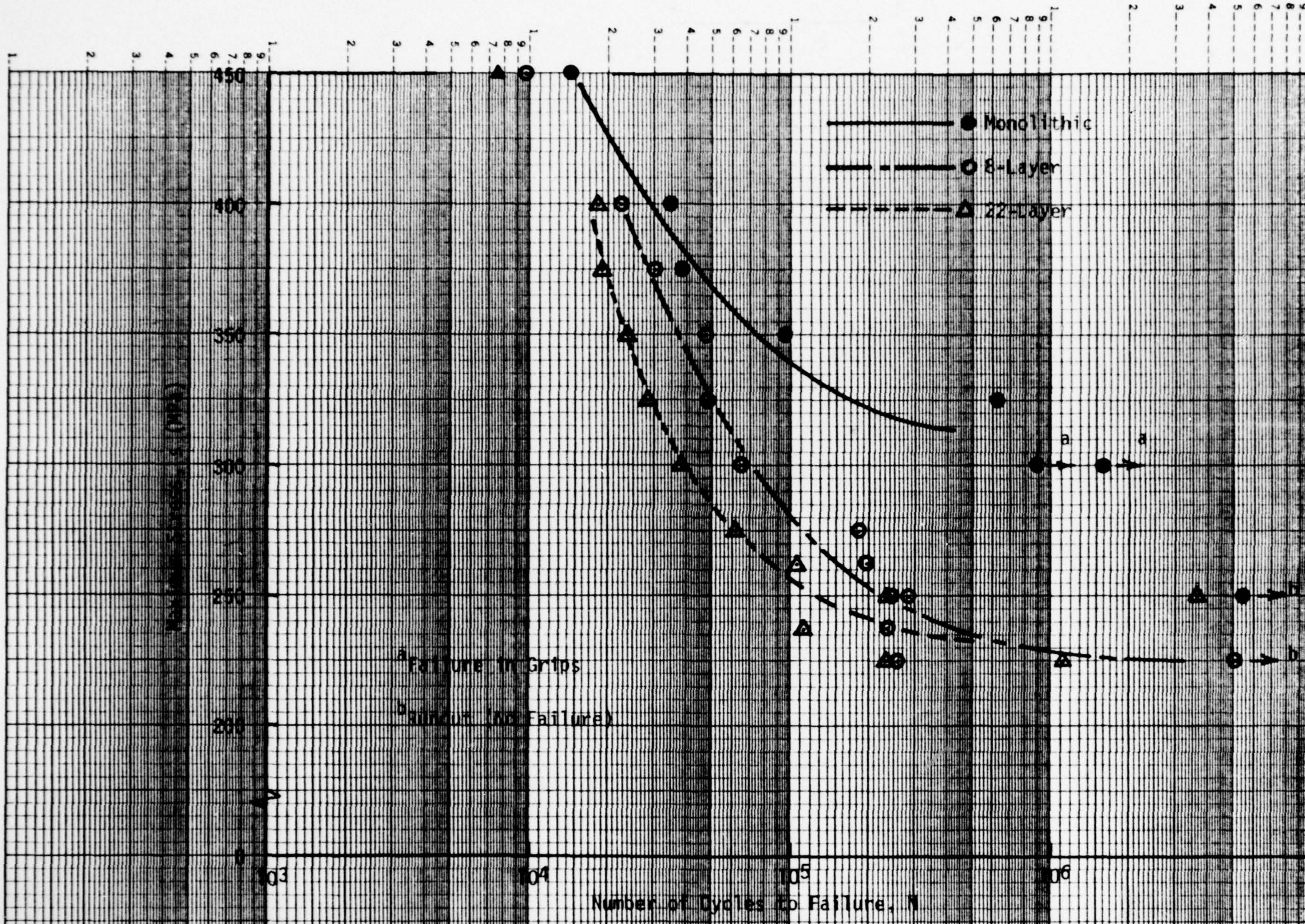

Fig. 14. Fatigue Lifetimes of Unnotched 8- and 22-Layer Laminates and of Monolithic 7075-T6 Aluminum Alloy. R = 0.1.

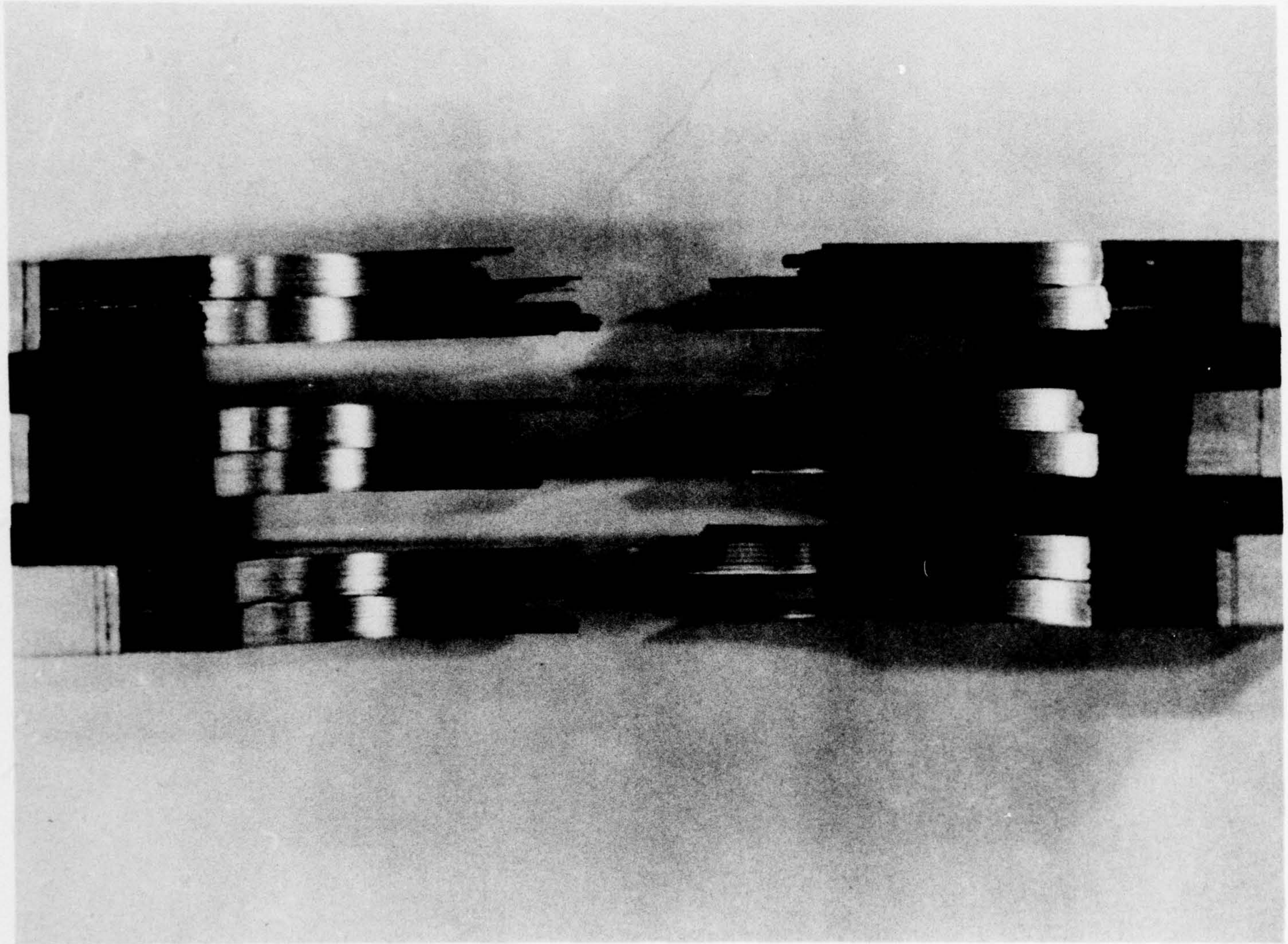

Fig. 15. Representative Failed Unnotched Laminates.

R = 0 [12]. The collection of data in Ref. 12 covers tests on several different batches of material at several different laboratories and contains considerable scatter. The results of Fig. 14, whether for monolithic specimens or for laminates, fall within or reasonably close (considering the difference in R values) to the scatterbands of Ref. 12. Thus at least part of the differences in Fig. 14 between lifetimes for monolithic and laminated specimens might be due to variations in the intrinsic fatigue properties of the three batches of 7075-T6 alloy represented by the three specimen types. Likewise, the generally poorer performance of the 22-layer laminates compared to the 8-layer laminates (Fig. 14) might have the same cause.

The results in Fig. 14 are at marked variance with previous tests on the same laminate systems for which the loading was fully-reversed (R = -1) 4-point plane bending [13,14]. In bending fatigue, both 8- and 22-layer laminates gave higher S-N curves than monolithic (clad) 7075-T6, with the 22-layer laminates superior to those having 8 layers [13,14]. This is the reverse of the trends shown in Fig. 14. However, only the 22-layer laminates were made from the same batch of material for both the bending and the axial load tests. The monolithic and 8-layer specimens each came from different batches of material. Thus the reversal in trends of the S-N curves for axial loading as compared to bending may again be at least partially a result of material variability. To investigate this possibility, a number of unnotched bending fatigue tests were run on monolithic specimens cut from the same plate as that used for the present work. These tests gave fatigue lifetimes substantially greater than for the plate used in the earlier comparisons of Ref. 12 and also greater than for any of the laminates tested earlier in bending. These observations, together with the previous discussion comparing Fig. 14 to the data trends in Ref. 12, tends to bear out the conclusion that at least some of the differences between the various types of specimens under the two sets of loading conditions are as much a reflection of material variability as of lamination. However, while this may be true for unnotched samples, it does not appear to be the case for notched fatigue, as discussed below.

One important difference between the earlier bending fatigue tests and the axial tests of the present work lies in the failure modes of the laminates. The bending tests were stopped short of final fracture because of the large deflections resulting after several laminae had broken. Complete fracture did of course occur in the axial load tests (Fig. 16). As in bending [13], laminates tested under axial loading tended to break at different locations along the specimen gage length in different layers, thus confirming the earlier conclusion of substantial decoupling of the fatigue processes in the various layers. There was, however, a tendency for cracks to originate at the junction between the 3 in. radii and the gage length of the specimen (Fig. 13). Observations of the failure of an 8-layer laminate at an intermediate load level--maximum stress 325 MPa (47,140 psi)--showed that most of the lifetime was consumed before any of the layers had cracked. The appearance of the first crack--which occurred in an interior layer--was closely followed by cracks in two other layers (one adjacent to the first layer to crack, one not) and then by final fracture. From the first observable crack to final failure took only 1850 cycles, while the total number of cycles to failure was 48,290. At such stress levels, cracking in any one layer results in enough load transfer to the uncracked layers that complete failure rapidly follows. Similar progressive failures were observed in notched laminates.

One interesting observation was the marked reduction in the severity of fretting in the grips for laminates. While a number of monolithic specimens broke prematurely in the grips because of fretting (Fig. 14; also true of notched monolithic specimens, Fig. 17), this did not occur for laminates. Furthermore the visible fretting scars were considerably less severe for laminates. This is probably a result of the compliance of the adhesive bonds, allowing the surface layer to move slightly with respect to the interior layers. This would take up some of the relative motion between the grips and the specimen which would otherwise--as in the monolithic specimens--occur entirely as slip at the specimen surface. The increased compliance of the laminates in the thickness direction would also change the contact pressure distribution at the faying surfaces. Both of these factors have a considerable influence on the formation of fatigue cracks by fretting processes.

3.2. Notched

The notched specimen geometry, Fig. 16, gives a theoretical stress concentration factor K_t of 2.42 based on net section stress [15]. S-N curves appear in Fig. 17, while typical failures are shown in Fig. 18.

As for the unnotched tests, Fig. 17 shows poorer performance for laminates than for monolithic 7075-T6, though the differences are smaller. Comparing the monolithic results in Fig. 17 with other published data for notched 7075-T6 at similar values of K_t and R [16,17] again indicates that the monolithic results are typical for this alloy.

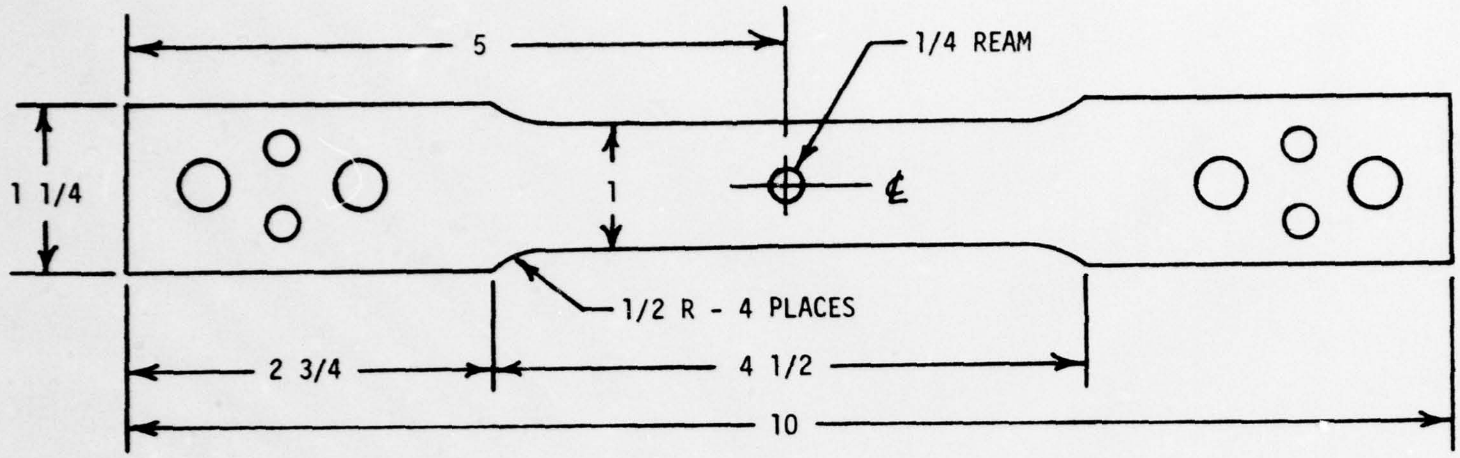

Fig. 16. Notched Fatigue Lifetime Test Specimen (dimensions in inches).

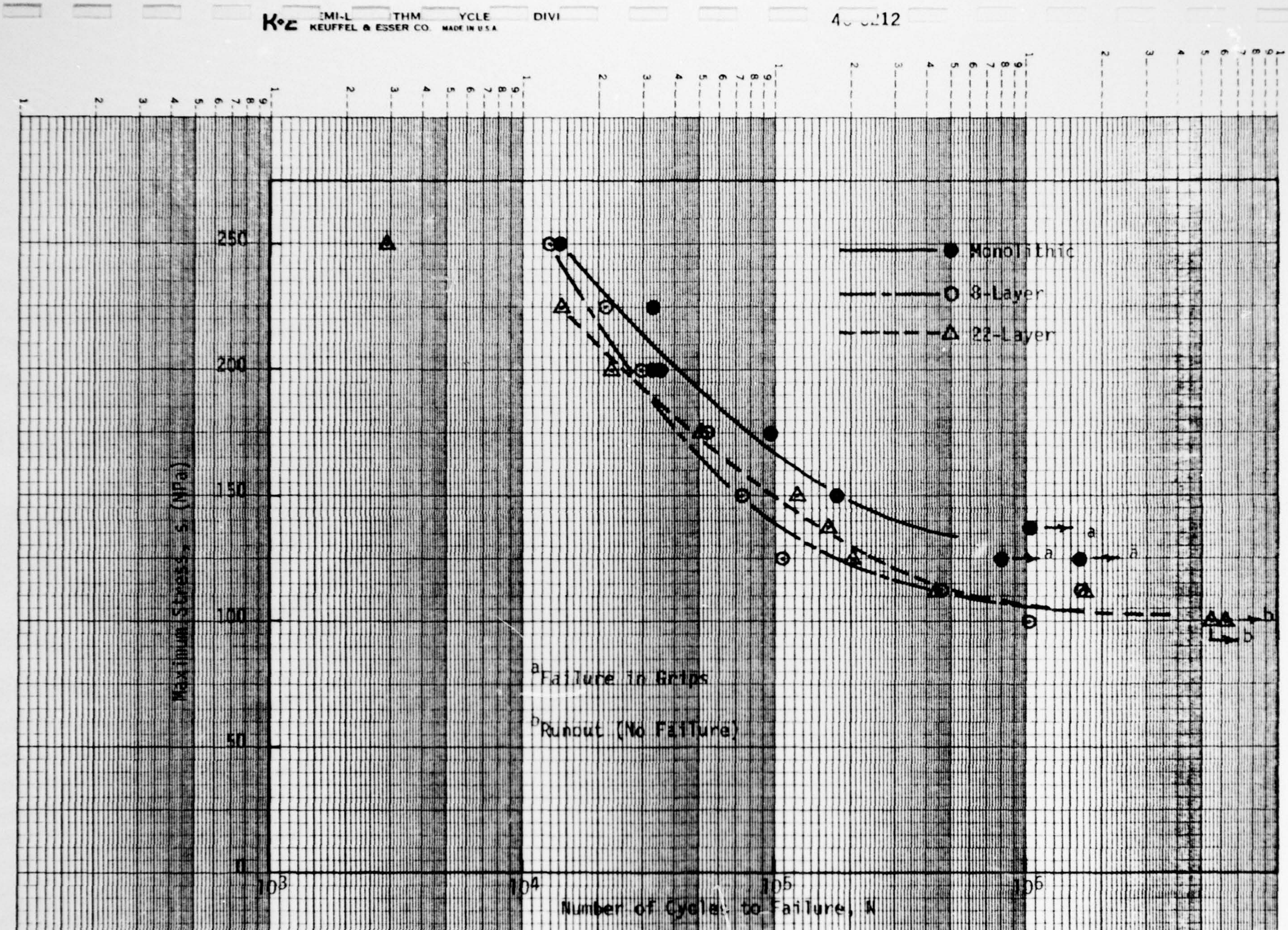

Fig. 17. Fatigue Lifetimes of Notched 8- and 22-Layer Laminates and of Monolithic 7075-T6 Aluminum Alloy. $R = 0.1$. $K_t = 2.42$.

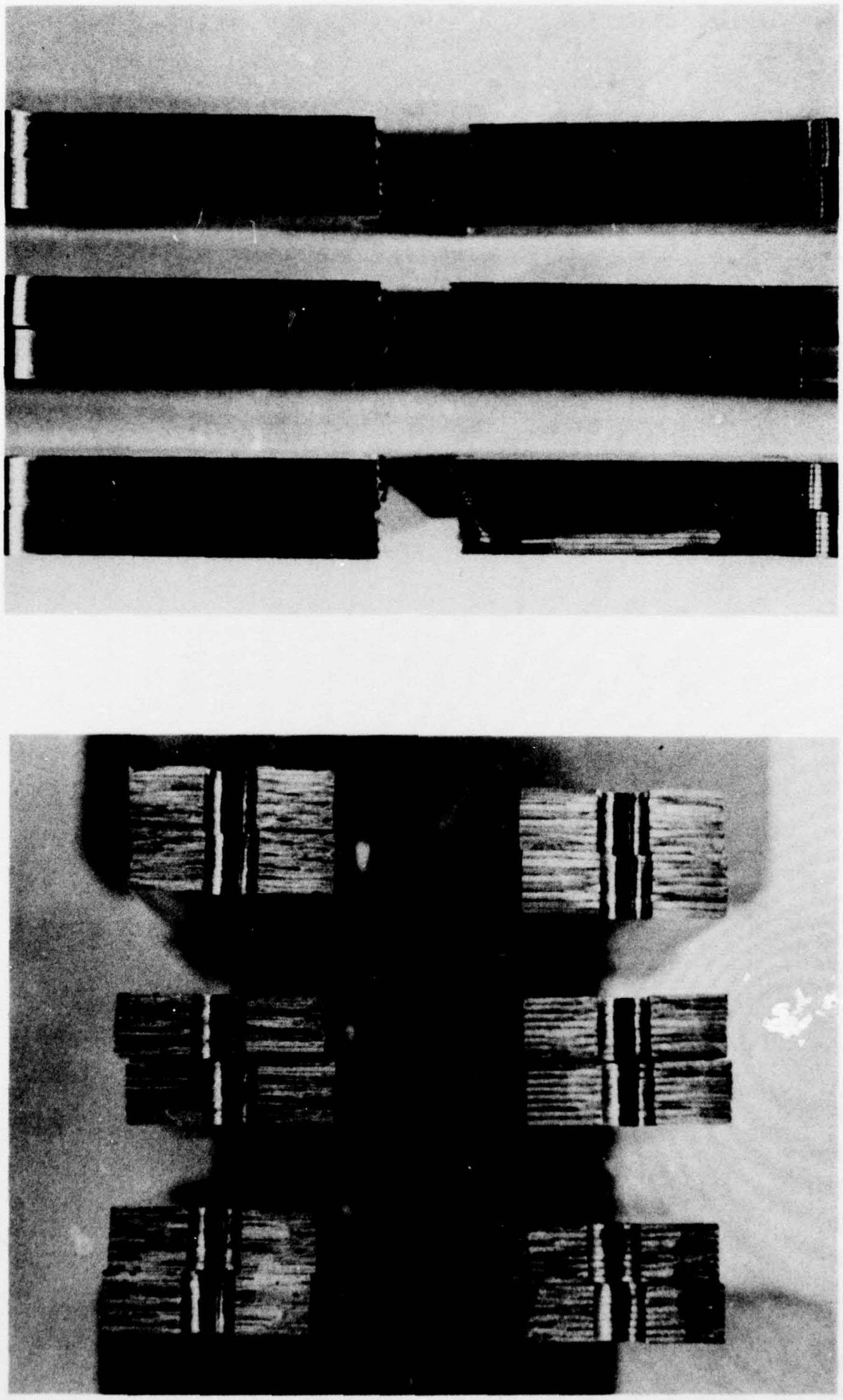

Fig. 18. Representative Failed Notched Laminates.

The trends in Fig. 17 are much the same as for the unnotched tests (Fig. 14), and again at some variance with those found previously for bending fatigue [14]. The bending tests reported upon in Ref. 14 included monolithic specimens made from the same 7075-T6 plate as for the present work. The notch geometry was essentially the same for the bending tests, although the K_t is somewhat less (1.9). Monolithic specimens gave fatigue lifetimes almost the same as laminates in bending--actually appearing intermediate between 8-layer laminates (shortest lives) and 22-layer laminate (longest lives) for most of the stress levels used [14]. Thus the inferiority of laminates in tension-tension fatigue cannot in this case be attributed solely to material variability. The fact that notched monolithic 7075-T6 specimens cut from the same plate were superior for axial loading but not for bending indicates that changing the type of loading may have unpredictable effects on the comparative fatigue performance of laminates.

The results for the notched tests (Fig. 17) show less scatter and are more closely grouped than for the unnotched tests (Fig. 14). Note also that it is only in the short life region where the ordering of the three materials is unambiguous (i.e., 22-layer poorest, 8-layer intermediate, monolithic best). In the long life region of Fig. 17 there is some indication that the 22-layer S-N curve may cross the 8-layer curve, the 22-layer laminates here showing lifetimes comparable to or longer than 8-layer laminates. The unnotched tests, Fig. 14, also show intermingling of the 8-layer and 22-layer data in the long life region. This is not surprising, as an early failure of 1 of 22 layers will increase the stress in the remaining layers much less than will early failure of 1 of 8 layers.

Fracture surfaces of notched laminates, Fig. 18, showed that cracking often originated in the interior layers. Sometimes, however, cracking appeared to have started in one of the surface layers, perhaps because of bending introduced during fabrication of the laminates. Some difficulty was also experienced in machining the 22-layer laminates, with the result that small burrs or nicks were occasionaly left at the edge of a hole. When present at the high stress regions 90° from the tensile axis, these were the crack initiation sites and may account in part for the 22-layer laminates having generally the shortest fatigue lives.

4. CONCLUSIONS AND RECOMMENDATIONS

a) Lamination has little overall effect on FCP in 7075-T6(51) crack divider laminates, where a through-crack exists perpendicular to the planes of the laminae. While any thickness effect on the FCP behavior of the base alloy can also be expected in weakly bonded laminates, such effects will generally be small. These comments can also be expected to apply to other alloy systems.

A case where lamina thickness might prove to be more important is that of load interaction effects. Thickness has been shown to affect the duration of retardation following high loads in monolithic materials, the retardation being greater in thin sections. A parallel trend would be expected in laminates, and study of retardation in laminates should be worthwhile.

Marked effects of lamination on fatigue behavior are also anticipated for other crack geometries--e.g., crack arrester laminates. Because practical application of laminates in structures will inevitably involve complex crack geometries, there is a need to investigate crack growth for such geometries--for example, a part-through crack in a laminate, perhaps at a hole or cutout--both analytically and experimentally.

b) Bi-material laminates combining two different aluminum alloys exhibited more complex FCP behavior than all-7075-T6(51) laminates. Here there appear to be interactions between the mechanisms of crack growth in the two materials. These lead to results which would not be predicted on a simple rule-of-mixtures basis. This points to the need for a better understanding of the micromechanisms of FCP in a general way, as well as suggesting possible methods of fabricating more fatigue-resistant structures by combining two or more alloys in appropriate fashion. Design of such structural laminates will require careful consideration not only of prospective lamina materials, but also of their relative thicknesses and locations with respect to probable flaw sites. Crack geometry considerations, as mentioned above, will also be relevant. One specific area which needs to be studied is the influence of an adverse environment on FCP in bi-material laminates of the type studied here. The 7075-T6 layers would be more drastically affected by an environment such as salt water than the 2024-T351 layers. This might cause the crack length differences between the layers to increase, altering the FCP behavior in unforeseen ways. It is also possible that such an environment would degrade the adhesive bond enough to affect the fatigue behavior.

c) Fatigue lifetimes of both notched and unnotched laminates were low compared to companion tests on monolithic 7075-T6 alloy. This is contrary to past results for bending fatigue and may in part reflect differences in the intrinsic fatigue characteristics of the various batches of material involved. Different layers of the laminates cracked at different points, as previously observed, demonstrating the independent nature of the fatigue process in the various layers.

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Fatigue crack propagation (FCP) and fatigue lifetime tests have been performed on several types of adhesively bonded aluminum alloy laminates. The laminate systems included several varieties of all-7075-T6(51) laminates--having 2, 4, 8 or 22 layers--as well as bi-material laminates combining 7075-T6 and 2024-T351 alloys. Among the conclusions of the study are: --FCP rates in crack divider laminates for which all layers are the same are comparable to those in the monolithic alloy. --FCP rates in bi-material 7075-T6/2024-T351 laminates are intermediate between those for the two alloys in monolithic form; over a

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considerable range of growth rates the bi-material laminates give FCP rates significantly lower than the averages of the two constituents. --Fatigue lifetimes of 7075-T6 8- and 22-layer laminates tested in tension-tension fatigue (R=0.1) are inferior to monolithic 7075-T6 alloy in either notched or unnotched forms; this is contrary to previous results for reversed bending.